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LENS ASSEMBLY AND OPTICAL IMAGING SYSTEM USING SAME

BACKGROUND OF INVENTION

1. Field of Invention

The present application relates to lens assemblies for use in optical imaging systems.

2. Discussion of Related Art

Lens assemblies for imaging objects are known. When designing lens assemblies, a designer may take into account one or more desired characteristics or constraints, such as focal length, back focal length, environment, spacing of lenses, aperture size, overall assembly length, field of view, cost and/or ease of manufacture, ease of use, or any other characteristics or design constraints.

However, it is often difficult to design a lens assembly that meets these sometimes competing design constraints, and this difficulty may be compounded when the lens assembly is intended to be used with additional components, or in specific applications. Examples of such additional components may be filters, lens covers, aperture stops, electronic detectors, electronic devices, or any other components. The resulting image quality produced by the lens assembly is often necessarily compromised in order to satisfy these many design constraints, or in order to achieve certain desired optical characteristics.

SUMMARY OF INVENTION

According to one aspect of the invention, a lens assembly for imaging an object is provided. The lens assembly comprises a plurality of lenses adapted to provide 1) a field of view of approximately 40 degrees, and 2) a distortion of less than approximately 1%.

Another aspect of the invention provides a lens assembly for imaging an object comprising a first lens group having at least one first lens element. The at least one first lens element has a first surface proximal to the object and second surface distal to the object. The lens assembly further comprises a second lens group having

at least one second lens element, the at least one second lens element having a first surface proximal to the object and second surface distal to the object. The lens assembly further comprises an aperture stop disposed between the first lens group and the second lens group, wherein the first and second lens groups are arranged to define a focal length, and wherein a distance between the first surface of the at least one first lens element and the second surface of the at least one second lens element is less than approximately 95% of the focal length.

According to one aspect of the invention, an optical system for imaging an object is provided comprising a lens assembly. The lens assembly comprises a plurality of lenses. The optical system further comprises at least one planar plate that introduces an aberration and is in optical communication with the lens assembly. The plurality of lenses is adapted to produce an aberration to compensate the aberration introduced by the at least one planar plate.

According to one aspect of the invention a lens system is provided. The lens system comprises, in order from an object side: a first meniscus lens; a second planar-convex lens; a third planar-concave lens; a fourth bi-concave lens; a fifth bi-convex lens; a sixth bi-convex lens; and a first planar plate.

According to yet another aspect of the invention, a lens system is provided. The lens system includes a plurality of lens elements and an aperture stop, each lens element having a lens surface defined by a radius of curvature (r), a thickness (T), and an index of refraction (n), the plurality of lens elements being spaced from each other by a distance (h). The lens system satisfies at least one of the following conditions:

$$1000 < r_4/r_2 \text{ or } r_4 = r_2 = \text{approximately infinity};$$

$$-0.56 < r_3/r_9 < -0.81;$$

$$0.9 < r_8/r_9 < 1.1 \text{ or } r_8 = r_9;$$

$$0.9 < r_{10}/r_{11} < 1.1 \text{ or } r_{10} = r_{11};$$

$$0.7 < (h_1+h_2)/(h_3+h_4) < 1.1;$$

$$0.95 < h_1+h_2+h_3+h_4+T_1+T_2+T_3+T_4+T_5+T_6 < f/1.02;$$

$$1.71 < n_{L1}, n_{L2}, n_{L5}, n_{L6} < 1.79; \text{ and}$$

$$1.67 < n_{L3}, n_{L4} < 1.81;$$

where:

r_2 represents a radius of curvature of an image side surface of a first lens element; r_3 represents a radius of curvature of an object side surface of a second lens element; r_4 represents a radius of curvature of an image side surface of the second lens element; r_8 represents a radius of curvature of an object side surface of a fifth lens element; r_9 represents a radius of curvature of an image side surface of the fifth lens element; r_{10} represents a radius of curvature of an object side surface of a sixth lens element; r_{11} represents a radius of curvature of an image side surface of the sixth lens element; h_1 represents a gap distance between the image side surface of the first lens element to the object side surface of the second lens element; h_2 represents a gap distance between the image side surface of a third lens element to the aperture stop; h_3 represents a gap distance between the aperture stop to an object side surface of a fourth lens element; h_4 represents a gap distance between the image side surface of the fifth lens element to the object side surface of the sixth lens element; T_1 represents a thickness of the first lens element; T_2 represents a thickness of the second lens element; T_3 represents a thickness of the third lens element; T_4 represents a thickness of the fourth lens element; T_5 represents a thickness of the fifth lens element; T_6 represents a thickness of the sixth lens element; n_{L1} represents an index of refraction of the first lens element; n_{L2} represents an index of refraction of the second lens element; n_{L3} represents an index of refraction of the third lens element; n_{L4} represents an index of refraction of the fourth lens element; n_{L5} represents an index of refraction of the fifth lens element; and n_{L6} represents an index of refraction of the sixth lens element.

According to yet another aspect of the invention, a lens assembly is provided. The lens assembly includes a plurality of lens elements, and an aperture stop having a size selected from a plurality of aperture stop sizes. The aperture stop optically cooperates with the plurality of lens elements regardless of the aperture stop size, such that a lens assembler may select an aperture stop for use with the lens assembly without reconfiguring a physical relationship of the plurality of lenses.

Various embodiments of the present invention provide certain advantages. Not all embodiments of the invention share the same advantages and those that do may not share them under all circumstances.

Further features and advantages of the present invention, as well as the structure of various embodiments of the present invention are described in detail below with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic representation of a lens assembly according to one aspect of the present invention.

Figure 2 is a cross-sectional representation of a first lens group of the lens assembly of Figure 1.

Figure 3 is a cross-sectional representation of a second lens group of the lens assembly of Figure 1.

Figure 4 is a cross-sectional representation of a third lens group of the lens assembly of Figure 1.

Figure 5 is a cross-sectional representation of a fourth lens group of the lens assembly of Figure 1.

Figure 6 is a cross-sectional representation of a housing for housing the lens assembly of Figure 1.

Figure 7 is a cross-sectional representation of the housing of Figure 6 with the lenses of the lens assembly of Figure 1.

Figures 8A and 8B illustrate an example of an aperture stop.

Figure 9 is an illustrative embodiment of values of aberrations associated with a lens assembly according to an aspect of the present invention.

Figure 10 illustrates the radius of curvature of a lens element.

DETAILED DESCRIPTION

According to aspects of the invention, the lens assembly is constructed to accommodate certain, often competing, design characteristics. In one aspect, the lens assembly provides high optical performance in a compact and easy to manufacture system (e.g., construct, assemble, and align). The lens assembly allows a manufacturer to produce a lens arrangement that is common among various aperture sizes so that manufacturability is enhanced. The lens assembly is also suitable for use in connection with additional components, such as filters and/or electronic detectors, such as CCD's and/or CMOS's.

In one aspect, the lens assembly is arranged to provide a relatively wide angle field of view, such as approximately 40 degrees, with minimal distortion, for example, less than 1%. The lens assembly according to this aspect may also be constructed to provide a ratio of the length of the lens assembly to the back focal length of approximately 1.39 to accommodate additional components, such as optical filters. In one embodiment the back focal length is 6 mm.

According to another aspect of the invention, the lens assembly is of a miniature and compact design, which may find suitable use as a security camera, an inspection camera, or as a personal use camera, as will be discussed in more detail below. One embodiment of a compact lens assembly has a focal length that is greater than the length of the lens assembly. The lens assembly may provide relatively high image quality without the need to space the lens elements by large distances, and without substantially increasing thicknesses of one or more of the lenses, thus enabling the compact design. For example, a distance between the first surface of the first lens element and the last surface of the last lens element is less than approximately 95% of the focal length. The lens assembly may be configured to be approximately 1/3 of an inch long.

According to one embodiment, the lens assembly is a four group, six element, lens assembly. The first lens group, nearest an object to be imaged, comprises a first lens have a convex surface proximate the object and a concave surface distal the object. The second lens group includes second and third lens elements, cemented together. The second lens element is a positive lens element, having a convex surface

proximate the object, and a planar surface distal the object. The third lens element is a negative lens element and has a planar surface proximate the object and a concave surface distal the object. The third lens group includes a fourth lens element cemented to a fifth lens element. The fourth lens element is a negative lens element and has a concave surface proximate the object and a concave surface distal the object. The fifth lens element is a positive lens element having a convex surface proximate the object and convex surface distal the object. The lens assembly also includes a sixth lens element, having convex surfaces proximate and distal the object to be imaged. In one embodiment, the above-listed lens elements are immediately adjacent each other. In one embodiment, an aperture stop (also referred to as aperture plate, aperture, stop, or micro-plate) is disposed between the second and third lens groups, and more specifically, between the third and fourth lens elements. In another embodiment, the aperture stop is disposed between the third and fourth lens elements, with the other lens elements being immediately adjacent each other.

The lens assembly may also incorporate filter plates, while maintaining a high quality image. The filter plates may be low-pass filter plates, color correction plates, or any other type of filter plate. In one embodiment, one or more parallel filter plates having planar surfaces may be disposed between the sixth lens element and the image plane. Such filter plates often produce aberrations, such as coma and astigmatism, or other aberrations, in the resulting image of the object. An aspect of the present application provides correction for such coma and astigmatism introduced by using plane parallel plates with a lens assembly. According to one embodiment, the lens assembly contains compensating aberrations to compensate the aberrations of plane parallel plates.

The structure of the lens assembly is nearly symmetric. A perfectly symmetric design departs from telecentricity. Certain electronic sensors or detectors may require some telecentricity provided by this optical design.

From a manufacturing perspective, the lens assembly may accommodate any one of a plurality of differently sized aperture stops without the need for re-arranging or re-designing the lenses, or their relationship to one another, while maintaining the desired characteristics of wide field of view and low distortion. In this manner, the

lens manufacturer can easily change the aperture stop as desired by the user while maintaining the lenses in a fixed relationship relative to each other. The aperture stop may be held relative to the lens assembly by one or more lenses. In this regard, the aperture stop may be held by physical contact with the one or more lenses.

The above aspects of the invention may be employed in any suitable combination as the present invention is not limited in this respect. Also, any or all of the above aspects may be employed in a relatively small imaging system; however, the present invention is not limited in this respect, as aspects of the invention may be used on any type of imaging system, including those that may be larger or smaller than the embodiments described. In addition, the lens assembly may be employed in any device and may be employed with any type of camera, including digital or film-based cameras. Various aspects and embodiments of the invention will now be described in more detail with respect to the accompanying figures. The invention is not, however, limited to the aspects and embodiments shown. In some of the figures that follow, specific numerical values are used to describe the elements and/or optical parameters. It should be appreciated that such values are not necessarily limiting, but rather, that the values may fall within a range of acceptable limits.

Figure 1 illustrates one embodiment of a lens assembly 17 according to the present invention. The lens assembly comprises four lens groups G_1 , G_2 , G_3 , and G_4 , arranged in order from an object side 19 to an image side 21. Lens group G_1 includes a single lens element L_1 . Lens group G_2 includes two lens elements, L_2 and L_3 . Lens group G_3 includes two lens elements, L_4 and L_5 . Lens group G_4 includes a single lens element L_6 . The lens assembly may also include an aperture stop 6 disposed between lenses L_3 and L_4 . In one embodiment, planar parallel plates F_1 and F_2 are disposed between lens L_6 and the image side 21 of the lens assembly 17. As an example, planar plate F_1 may be cover glass (e.g., for covering the detector (not shown)), while planar plate F_2 may be a low-pass filter. Planar plates F_1 and F_2 may alternatively be any planar parallel plates. Surfaces 12, 13, 14, and 15 are all planar, and thus each has a near infinite radius of curvature. The thicknesses, T , and gap distances, h , of Figure 1 are described in more detail in what follows.

The introduction of planar parallel plates, such as F_1 and F_2 in Figure 1, into an optical system may introduce aberrations into the system. However, such planar plates may be necessary for use with CCD or CMOS devices. A lens assembly which is designed in the absence of planar parallel plates may suffer performance degradation if one or more planar parallel plates are subsequently inserted into the assembly. To achieve satisfactory performance, it may be necessary to design the lens assembly to compensate for such aberrations, so that a satisfactory image quality may result with the use of the planar plates. Thus, according to one aspect of the invention, as will be described in more detail below, the combination of lenses L_1 - L_6 compensates for any aberrations introduced by the planar parallel plates F_1 and F_2 .

In the following description, radii of curvature are listed for several surfaces of lens elements. As is conventional, the radii will be listed with a positive value when the surface bows toward an object side of the lens, and with a negative value when the surface bows toward an image side of the lens. Also, the numerical values discussed in connection with Figures 2-6 correspond to an assembly designed for use with a 1/3 inch CCD device while providing approximately 40 degree field of view. It should be appreciated that the values will differ if the lenses are scaled for use with another device, as will be mentioned in relation to Tables 3-9. Such scaling of components is meant to be encompassed within the present invention. The following embodiment reflects a lens assembly having an 8.36 mm focal length. However, as will be seen below, other suitable focal lengths may be employed, such as 10 mm.

Lens L_1 , the cross-section of which is shown in more detail in Figure 2, includes a convex surface 1 facing toward the object side 19 of the lens assembly 17, and having a radius of curvature of approximately 7.67 mm. Lens L_1 also includes a concave surface 2 facing toward the image side 21 of the lens assembly 17, and having a radius of curvature of approximately 40.46 mm. The thickness T_1 of the lens, measured from the vertex 24 of the object side surface 1 to the vertex 26 of the image side surface 2 is approximately 0.895 mm. The lens is circular with a diameter D_1 of approximately 5 mm. In one embodiment, the lens is made of glass, with an index of refraction, N_d , of approximately 1.788309, and a dispersion, v , of approximately 47.47. However, it should be appreciated that the present invention is

not limited in this respect, as other suitable materials and/or other suitable indexes of refraction and/or dispersion may be employed. Both the object side surface 1 and image side surface 2 are coated with approximately $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect.

Figure 3 is a cross-sectional view of the second lens group G_2 of Figure 1. The second lens group G_2 includes lenses L_2 and L_3 , which are cemented together, and share a common planar mid-surface 4. Lens L_2 includes a convex surface 3 facing toward the object side 19 of the lens assembly 17, and having a radius of curvature of approximately 3.72 mm. The object side surface 3 is coated with approximately $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect. The thickness T_2 of lens L_2 , as measured from the vertex 34 of the object side surface 3 to the shared mid-surface 4 of lens group G_2 , is approximately 1.19 mm. Lens L_2 is circular and has a diameter D_2 of approximately 4 mm. Lens L_2 is made of glass, and has an index of refraction, N_d , of approximately 1.744002 and a dispersion, v , of approximately 44.72. However, it should be appreciated that the present invention is not limited in this respect, as other suitable materials and/or other suitable indexes of refraction and/or dispersion may be employed.

Lens L_3 has a concave surface 5 facing toward the image side 21 of the lens assembly 17, and having a radius of curvature of approximately 2.4 mm. The image side surface 5 is coated with approximately $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect. The thickness T_3 of lens L_3 , measured from the vertex 38 of image side surface 5 to the shared mid-surface 4 of lens group G_2 is approximately 0.6 mm. As with lens L_2 , lens L_3 is circular and has a diameter D_3 of approximately 4 mm. Lens L_3 is made of glass and has an index of refraction, N_d , of approximately 1.717360 and a dispersion, v , of approximately 29.51. However, it should be appreciated that the present invention is not limited in this respect, as other suitable materials and/or other suitable indexes of refraction and/or dispersion may be employed. Lenses L_2 and L_3 may be cemented together by any suitable means, as

may be known in the art, for example UV epoxy. However, it should be appreciated that the invention is not limited in this regard.

Figure 4 illustrates a cross-sectional view of lens group G_3 of Figure 1, including lenses L_4 and L_5 . Lenses L_4 and L_5 are cemented together, and thus share a common mid-surface 8 having a radius of curvature of approximately 6.635 mm (which is concave on lens L_4 and convex on lens L_5). Lens L_4 also includes a concave surface 7 facing toward the object side 19 of the lens assembly 17, and having a radius of curvature of approximately -4.36 mm. The left surface of lens L_4 is coated with approximately $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect. The thickness T_4 of lens L_4 , measured from the vertex 44 of the object side surface 7 to the vertex 46 of the shared mid-surface 8 is approximately 0.58 mm. Lens L_4 is circular with a diameter D_4 of approximately 3.5 mm. Lens L_4 is made of glass, and has an index of refraction, N_d , of approximately 1.672697 and a dispersion, v , of approximately 32.21. However, it should be appreciated that the present invention is not limited in this respect, as other suitable materials and/or other suitable indexes of refraction and/or dispersion may be employed.

Lens L_5 includes a convex surface 9 facing toward the image side 21 of the lens assembly 17, and having a radius of curvature of approximately -6.635 mm. The image side surface 9 of lens L_5 is coated with $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect. The thickness T_5 of lens L_5 , measured from the vertex 50 of the image side surface 9 to the vertex 46 of the common mid-surface 8 is approximately 1 mm. Lens L_5 is circular with a diameter D_5 of approximately 3.5 mm. In one embodiment, lens L_5 is made of glass, and has an index of refraction, N_d , of approximately 1.744002 and a dispersion, v , of approximately 44.72. However, it should be appreciated that the present invention is not limited in this respect, as other suitable materials and/or other suitable indexes of refraction and/or dispersion may be employed. Lenses L_4 and L_5 may be cemented together by any suitable means, as may be known in the art, for example UV epoxy. However, it should be appreciated that the invention is not limited in this regard.

Figure 5 is a cross-sectional view of lens group G_4 of Figure 1, which includes lens L_6 . Lens L_6 has a convex surface 10 facing toward the object side 19 of the lens assembly 17, and having a radius of curvature of approximately 13 mm. The object side surface 10 is coated with approximately $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect. Lens L_6 also has a convex surface 11 facing toward the image side 21 of the lens assembly 17, and having a radius of curvature of approximately -13 mm. The image side surface 10 is also coated with approximately $0.5876\ \mu\text{m}$ of Ar, although other suitable coatings (or no coating at all) may be employed, as the present invention is not limited in this respect. The thickness T_6 of lens L_6 , measured from the vertex 64 of the object side surface 10 to the vertex 66 of the image side surface 11 is approximately 1.89 mm. Lens L_6 is circular with a diameter D_6 of approximately 4.5 mm. Lens L_6 is made of glass, with an index of refraction, N_d , of approximately 1.713003 and a dispersion, v , of approximately 53.83. However, it should be appreciated that the present invention is not limited in this respect, as other suitable materials and/or other suitable indexes of refraction and/or dispersion may be employed.

The distances shown in Figure 1 should be controlled to ensure satisfactory performance of the lens assembly. Distance h_1 is the gap distance from the vertex 26 of surface 2 to the vertex 34 of surface 3. Gap distance h_2 is the distance from vertex 38 of surface 5 to the plane of the aperture stop 6, indicated in Figure 1. Gap distance h_3 is measured from plane of the aperture stop 6 to the vertex 44 of surface 7. Gap distance h_4 is measured from the vertex 50 of surface 9 to the vertex 64 of surface 10. Gap distance h_5 is measured from the vertex 66 of surface 11 to the surface 12. Gap distance h_6 is measured from the surface 13 to the surface 14, and gap distance h_7 is measured from the surface 15 to an image plane, as shown in Figure 1. Satisfactory performance is maintained by the lens assembly 17 for any values of h_5 , h_6 , h_7 , and the thicknesses of the planar plates, T_{F1} , and T_{F2} , provided the following relationship is approximately observed: $1\text{mm} \leq T_{F1} + T_{F2} \leq 3\text{mm}$, and the total thickness of $h_5 + h_6 + h_7 + T_{F1} + T_{F2}$ is less than or equal to the total back focal length of the lens assembly, as would be known to one of skill in the art.

According to one aspect of the invention, a housing 70 is provided to hold the lenses L_1 - L_6 of Figure 1, and to ensure the values of h_1 , h_2 , h_3 , and h_4 are maintained appropriately. The housing 70, in the absence of the lenses, is shown in cross-sectional view in Figure 6. In one embodiment, the housing 70 includes ten step locations, S_1 - S_{10} . The steps are formed in the housing for the purpose of receiving the lenses L_1 - L_6 and an aperture stop, and ease the process of assembling the lenses L_1 - L_6 . The length and diameter of each step location is shown in Table 1. The lengths are given relative to the x-axis in Figure 6, and the diameters relative to the y-axis. Some of the step locations have more than one diameter, in which case Table 1 below indicates the minimum diameter. The length of the housing is approximately 7.4 mm. The following data is for the invention scaled to 8.36 mm focal length.

Table 1: Housing Step Sizes		
Step Number	Step Length (mm)	Step Diameter (mm)
S_1	0.60	5.76*
S_2	0.34	5.76
S_3	0.38	5.02
S_4	1.14	4.51
S_5	1.14	4.02
S_6	1.14	3.51
S_7	0.94	4.01
S_8	0.76	4.52
S_9	0.41	5.27
S_{10}	0.65	5.27*
* The listed value corresponds to the minimum diameter of the step.		

The housing 70 may be formed with threads to allow the housing to be threaded in and held relative to another component, such as a camera housing. In one embodiment, the housing is formed with an M9 thread, having, e.g., an outer diameter of approximately 8.9 mm and a pitch diameter of approximately 8.6 mm. Of course,

other suitable thread configurations or other suitable attaching arrangements may be employed, as the present invention is not limited in this respect. Wrench flats 76 may be formed along the length of the housing, or as shown, along a portion of the housing to facilitate threading the housing to the other component. The width across the wrench flats is approximately 7 mm. Other suitable arrangements to facilitate threading the housing, such as, e.g., spanner wrench slots, may be employed, as the present invention is not limited in this respect.

In one embodiment, the housing is formed of metal. However, it should be appreciated that the housing could be formed out of any material, including plastics, ceramics, or any other type of material, as the invention is not limited in this regard.

Figure 7 is a cross-sectional view of the lens groups G_1 , G_2 , G_3 , and G_4 , of Figure 1 within the housing 70 of Figure 6. It should be appreciated that housing 70 shown in Figure 7 is rotated at 90 degrees relative to the view in Figure 6, so that the wrench flats 76 are not evident.

In one embodiment, an aperture stop 78, described in further detail below, may be disposed in step S_5 of the housing. Lens group G_2 may be disposed in step S_5 so as to contact the aperture stop 78, thereby enhancing holding the aperture stop in the housing. Lens group G_3 is disposed in step S_6 of the housing, and may also contact the aperture stop. Of course, the aperture stop may be held in place by other suitable arrangements, as the present invention is not limited in this respect. Lens group G_1 is disposed in step S_3 of the housing, and lens group G_4 is disposed in step S_8 of the housing. By using the step locations in the housing, the lens groups G_1 - G_4 are spaced appropriately to ensure proper function of the lens assembly. In other words, the distances h_1 , h_2 , h_3 , and h_4 are maintained at appropriate values.

The lens groups may fit snugly within the housing steps, or may be secured within the housing by any means, for instance glue or other suitable adhesive.

Figures 8A and 8B show an aperture stop 78 that may be used in combination with lenses L_1 - L_6 of Figure 1. As discussed above, the aperture stop may be disposed between lenses L_3 and L_4 , as shown in Figure 7. The aperture stop 78 may be a plate with a circular opening in the center. The plate may be formed of aluminum and may include a surface finish of BI-Fluoride etch followed by type 2 black anodize. Other

materials and finishes may be used for the plate, and the invention is not limited in this regard.

Figure 8A illustrates a front-on view of the micro-plate, which has a circular outer diameter, d_o , of approximately 4 mm, and a flat edge at approximately 1.88 mm from the center of the micro-plate. The size of the aperture stop, which may also be designated by f number, corresponds to the diameter d_i of the central circular opening and may be any one of several values, as listed in Table 2, for example. According to an aspect of the invention, any of the values listed in Table 2 may be used without needing to reposition the lenses L_1 - L_6 relative to each other. In other words, the performance of the lens assembly remains within satisfactory limits for any of the aperture sizes.

Figure 8B illustrates a side view of the micro-plate of Figure 8A. In one embodiment, the thickness of the plate is approximately 0.127 mm, although other suitable thicknesses may be employed as the present invention is not limited in this respect. The following data is for the invention scaled to 8.36 mm focal length.

Table 2: Aperture Stop Size		
f number	Outer Diameter (mm)	Inner Diameter (mm)
f11	4	0.48
f8	4	0.66
f5.6	4	0.95
f4	4	1.33
f2.8	4	1.89

As discussed above, an aspect of the present application provides correction for coma and astigmatism that may be introduced by using plane parallel plates with a lens assembly. According to one embodiment, the lens assembly includes compensating aberrations to compensate the aberrations of plane parallel plates. Figure 9 is a non-limiting example of values of Seidel aberration coefficients, in units of waves, of seven types of aberrations that may be introduced in the lens assembly

according to the present invention. Values are listed for each surface of the lenses, 1-5 and 7-11, the aperture stop 6, as well as the surfaces 12-15 of two the planar plates F_1 and F_2 (the combination of which is referred to as a “window” in Figure 9). In the embodiment described herein, the two planar plates include one cover glass and one low-pass filter. The seven types of aberrations listed are spherical aberration, coma, astigmatism, field curvature, distortion, longitudinal chromatic aberration, and tangential chromatic aberration. Diffraction is not listed, as it is a second order effect in the system due to the range of aperture stop sizes used.

The total values listed for each type of aberration are computed by a sum of the “lens total” value and the “window total” value. The aperture stop and the image do not contribute to the seven listed types of aberrations of the system, as indicated by the values of zero in the appropriate rows. In one embodiment, the lens assembly is a double-Gauss lens assembly. It can be seen that the double-Gauss lens assembly produces compensating aberrations to compensate for the aberrations of the planar plates. The lens design thus produces a satisfactory image quality for any window wherein the thickness of the window, $T_{F1}+T_{F2}$, is approximately within the range of 1-3 mm. Thus, the lens design allows the user to choose the specific types of planar plates, such as filters, cover glass, etc., for the desired application.

It will be appreciated that while specific values for radii of curvature, index of refraction, and dispersion of the lens elements have been listed in connection with Figures 1-5, there exists a range of values within which each parameter may fall while still providing satisfactory performance of the lens assembly. The values corresponding to additional embodiments are shown in Tables 3-9. The values of T_{F1} , T_{F2} , h_5 , h_6 , and h_7 are not listed since, as mentioned previously, satisfactory image quality is obtained as long as the following relationship is approximately observed: $1\text{ mm} \leq T_{F1}+T_{F2} \leq 3\text{ mm}$, and the total thickness of $h_5+h_6+h_7+T_{F1}+T_{F2}$ is less than or equal to the total back focal length of the lens assembly. It should be appreciated that the values listed in Tables 3-9 correspond to a lens assembly having a focal length, f , of 10 mm. As is known to those of skill in the art, the listed values in Tables 3-9 will change in a known way if the lens assembly is scaled to a focal length other than 10 mm. Thus, the values could be scaled to enable use with CCD or CMOS devices of

varying dimension, while maintaining approximately a 40 degree field of view. The present invention is meant to encompass such alterations attained by scaling of the lens assembly. It should also be noted that for the embodiments of Tables 3-9, the step locations of the housing 70 of Figure 6 may need to be altered to maintain the proper gap distances, if the housing were to be used to hold the lens assembly. Also note that in Tables 3-9 the listed thicknesses correspond to the axial distance to the next surface.

Table 3: Prescription 1 For $f=10$ mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	9.172	1.070	1.788	47.47
2	48.384	0.161	1	
3	4.449	1.423	1.744	44.72
4	Infinity	0.718	1.717	29.51
5	2.870	0.369	1	
6	Infinity	0.435	Aperture stop	
7	-5.214	0.694	1.673	32.21
8	7.935	1.196	1.744	44.72
9	-7.935	0.126	1	
10	15.546	2.260	1.713	53.83
11	-15.546			

Table 4: Prescription 2 For $f=10$ mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	9.534	1.064	1.744	44.72
2	55.149	0.113	1	
3	4.495	1.429	1.744	44.72
4	Infinity	0.721	1.673	32.25
5	2.848	0.370	1	
6	Infinity	0.437	Aperture	

7	-4.830	0.697	1.673	32.25
8	7.089	1.200	1.744	44.72
9	-7.089	0.126	1	
10	17.624	2.268	1.744	44.72
11	-17.624			

Table 5: Prescription 3 For f=10 mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	9.222	1.076007	1.757	47.81
2	56.061	0.054011	1	
3	4.419	1.422968	1.717	47.96
4	Infinity	0.717463	1.673	32.25
5	2.839	0.368895	1	
6	Infinity	0.434663	Aperture	
7	-5.014	0.693547	1.673	32.25
8	7.383	1.195772	1.717	47.96
9	-7.383	0.125556	1	
10	16.689	2.170737	1.757	47.81
11	-16.689			

Table 6: Prescription 4 For f=10 mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	9.067	1.096	1.757	47.81
2	57.422	0.056	1	
3	4.429	1.375	1.717	47.96
4	Infinity	0.723	1.673	32.25
5	2.843	0.372	1	
6	Infinity	0.438	Aperture	
7	-5.047	0.699	1.673	32.25
8	7.411	1.250	1.717	47.96
9	-7.411	0.127	1	
10	17.285	2.255	1.773	49.62

11	-17.285			
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Table 7: Prescription 5 For f=10 mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	9.294	1.090	1.757	47.81
2	59.204	0.042	1	
3	4.443	1.433	1.717	47.96
4	Infinity	0.723	1.673	32.25
5	2.853	0.372	1	
6	Infinity	0.438	Aperture	
7	-5.057	0.698	1.673	32.25
8	7.457	1.204	1.717	47.96
9	-7.457	0.126	1	
10	16.987	2.271	1.773	49.57
11	-16.987			

Table 8: Prescription 6 For f=10 mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	10.109	1.178	1.744	44.72
2	Infinity	0.024	1	
3	4.593	1.272	1.744	44.72
4	Infinity	0.718	1.750	34.95
5	3.109	0.369	1	
6	Infinity	0.435	Aperture	
7	-4.404	0.695	1.717	29.51
8	5.733	1.673	1.744	44.72
9	-5.733	0.126	1	
10	19.846	1.178	1.744	44.72
11	-19.846			

Table 9: Prescription 7 For $f=10$ mm

Surface	Radius of Curvature r (mm)	Thickness (mm)	Refractive Index (Nd)	Abbe No. (Vd)
1	10.427	1.487	1.717	47.96
2	Infinity	0.242	1	
3	4.224	1.311	1.744	44.72
4	Infinity	0.705	1.801	35.08
5	2.983	0.366	1	
6	Infinity	0.431	Aperture	
7	-4.461	0.695	1.673	32.21
8	6.205	1.352	1.744	44.72
9	-6.205	0.125	1	
10	17.516	1.487	1.744	44.72
11	-17.516			

In a more general sense, the design of the lens assembly of Figure 1, according to the present invention, may obey any, all, or any combination of the relationships shown in Table 10. For purposes of this table, the radii of curvature of the respective surfaces of each of the lens elements are indicated by the notation r_1, r_2 , etc. As an example, Figure 10 illustrates the radius of curvature, r_1 , of surface 1 of lens L_1 of Figure 1. In Table 10, the indices of refraction for the respective lens elements are indicated by the notation n_{L1}, n_{L2} , etc., and the focal length of the lens assembly is represented by the symbol f .

Table 10: Ratios and Relationships For Lens Assembly For $f=10$ mm

Radii of Curvature
$1000 < r_4/r_2$ or $r_4=r_2=$ approximately infinity
$-0.56 < r_3/r_9 < -0.81$
$0.9 < r_8/r_9 < 1.1$ or $r_8=r_9$
$0.9 < r_{10}/r_{11} < 1.1$ or $r_{10}=r_{11}$
Distances/Thicknesses
$0.7 < (h_1+h_2)/(h_3+h_4) < 1.1$
$0.95 < h_1+h_2+h_3+h_4+T_1+T_2+T_3+T_4+T_5+T_6 < f/1.02$
Indices of Refraction
$1.71 < n_{L1}, n_{L2}, n_{L5}, n_{L6} < 1.79$
$1.67 < n_{L3}, n_{L4} < 1.81$

The lens assemblies described herein may be used in various applications and environments. For example, one field of use may be security cameras. Security cameras may be used in banks, casinos, retail stores, personal property, yards, airports, sports and entertainment arenas, theaters, restaurants, cars, office buildings, gas stations, security checkpoints, boarder or other boundary crossings, transportation vehicles and terminals, such as trains and train stations, ships and docks, buses and bus depots, military installations, etc. as the present invention is not limited in this respect.

The lens assemblies described herein may also be used for industrial applications. Examples of this sort of use may include flexible bore scopes with a distal chip, cameras for insertion into wells, cameras for viewing engines (such as aircraft engines) and engine parts, cameras for viewing under buildings or cars, cameras used for measurement, or any other industrial application.

The lens assemblies described herein may also be used for personal or business applications. Examples of this sort may include personal cameras, digital cameras, phone cameras, web cameras, disposable cameras, videography, or any other type of camera or system.

The lens assemblies described herein may also be used for medical applications. For example, the lens assemblies may be used for endoscopy with a distal chip, dental procedures, gynecological exams, ear/nose/throat exams, distal chip colonoscopy, distal chip laparoscopy, or any other medical procedures or uses.

Other applications will be readily apparent to those of skill.

Having thus described several aspects of at least one embodiment of this invention, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Further, although each embodiment described above includes certain features, the invention is not limited in this respect. Thus, one or more of the above-described or other features of the lens assembly, may be

employed singularly or in any suitable combination, as the present invention is not limited to a specific embodiment. Accordingly, the foregoing description and drawings are by way of example only.

What is claimed is: